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Mesoscale Aspects of Numerical Modeling of Climate

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Goal and main objectives of climate modeling

Goal: development of (e.g. national) expert system for scientifically grounded forecasts of climate change on global and regional scales and for assessing consequences of climate change for environment and human society.

Main objectives:

1. the reproduction of the present-day climate (understanding physics of climate);
2. the assessment of possible climate changes under the influence of small external forcing (sensitivity of the climate system);
3. the forecast of climate change and assessing its impact on environment and society.

Objectives of climate modeling

- **To reproduce both "climatology" (seasonal and monthly means) and statistics of variability: intra-seasonal (monsoon cycle, characteristics of storm-tracks, etc.) and climatic (dominated modes of inter-annual variability such as El-Nino phenomenon or Arctic Oscillation)**

- **To estimate climate change due to anthropogenic activity**

- **To reproduce with high degree of details regional climate: features of hydrological cycle, extreme events, impact of global climate change on regional climate, environment and socio-economic relationships**

Regional scale modeling and assessment

- **Atmospheric modeling, e.g. using global climate model with improved spatial resolution in the region under consideration and non-hydrostatic mesoscale models: parameterization of mesoscale variability**

- **Vegetation modeling, e.g. models of vegetation dynamics: parameterization of biogeochemical and hydrological cycles**

- **Soil (including permafrost) modeling, e.g. models of snow and frozen ground mechanics: parameterization of hydrological and biogeochemical cycles**

Regional scale modeling and assessment

- **Catchment modeling, e.g. constructing models of river and lakes dynamics: parameterization of hydrological cycle**
- **Coupled regional models**
- **Air and water quality modeling**
- **Statistical and dynamic downscaling (e.g. regional projections of global climate change patterns)**

Objectives of climate modeling

- **Fundamental question (V.P. Dymnikov): what climatic parameters and in what accuracy must by reproduced by a mathematical model of the climate system to make its sensitivity to small perturbations of external forcing close to the sensitivity of the actual climate system?**

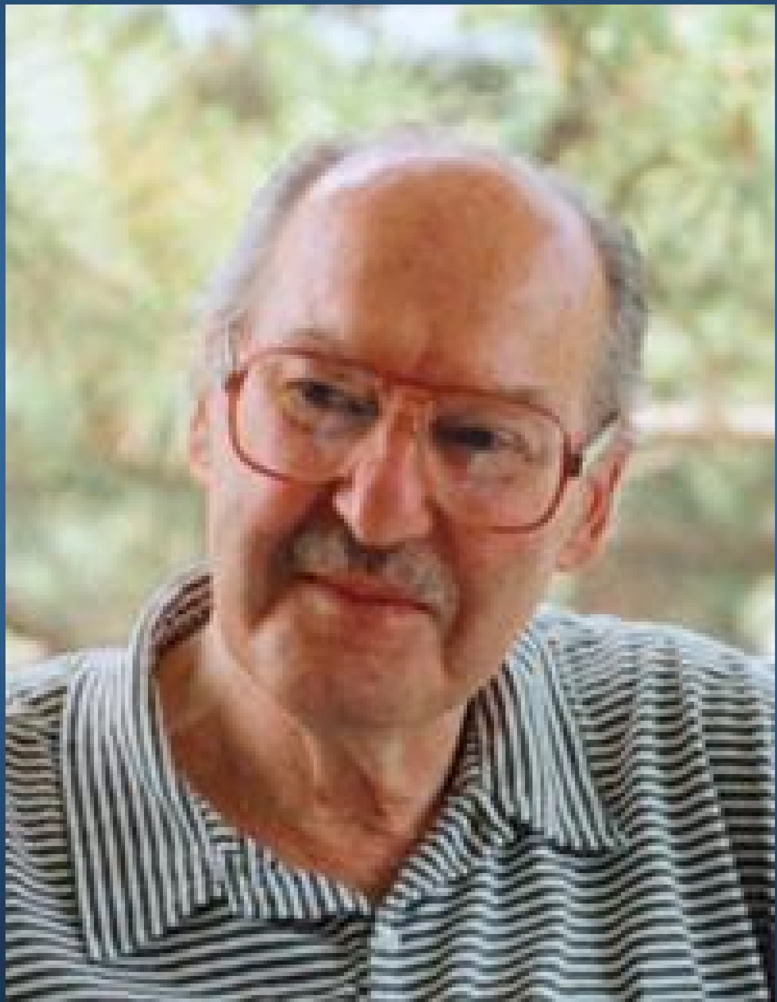
John von Neumann (1903 – 1957)

J.G. Charney, R. Fjortoft, J. von Neuman. "Numerical integration of the barotropic equation", 1950, Tellus, 2, 237-254.

John von Neumann had recognized weather prediction as a prime candidate for application of electronic computers. In early 1948 he invited Jule Charney to head the meteorology group in his Electronic Computer Project.

Joseph Smagorinsky (1924 – 2005)

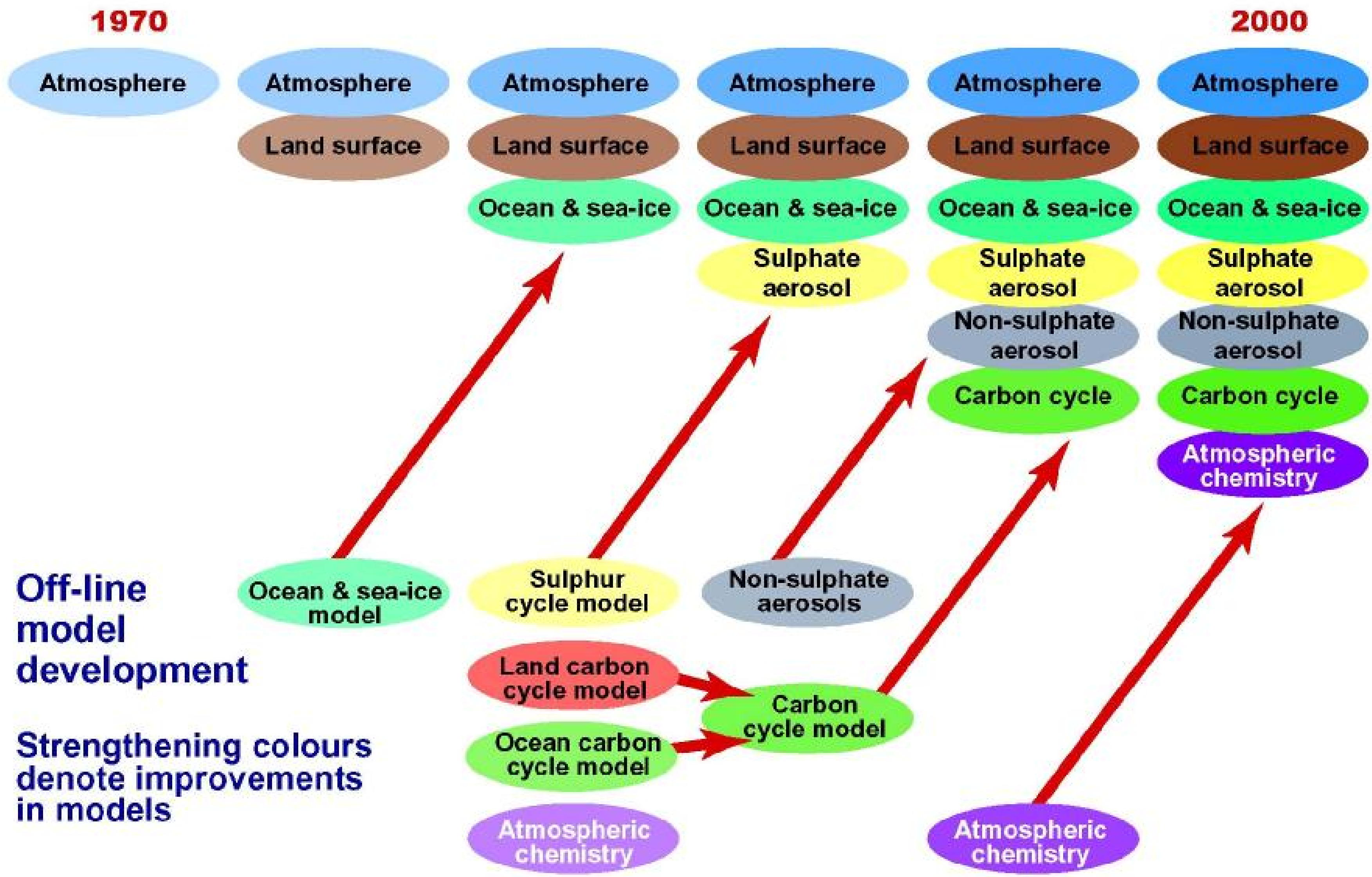
“General circulation experiments with the primitive equations. 1. Basic experiment", 1963, Mon. Wea. Rev., 91, 98-164.



- Smagorinsky's key insight was that the increasing power of computers would allow one to move toward the simulation of the Earth's climate.
- Smagorinsky guided the development of the first model of atmospheric general circulation taking into account basic nonadiabatic factors.

Guri Ivanovich Marchuk
G.I. Marchuk. “Numerical methods in weather forecasting”, 1967

Towards Comprehensive Earth System Models



General CirculationModel of the Atmosphere and Ocean
Novosibirsk Computer Center
(Marchuk et al., 1980)

- **Coupled model based on the implicit scheme and splitting-up method in time. Synchronization of thermal relaxation times (1 «atmospheric» year = 100 «oceanic» years). The atmospheric resolution: 10x6 degrees in longitude and latitude, 3 levels in vertical up to 14 km (3240 grid points). Time step: 40 min. The oceanic resolution: 5x5 degrees and 4 levels (7200 grid points). Time step: 2 days.**

- **A single experiment: mean-January circulation, for calculations on 40 model «atmospheric» days (11 «oceanic» years) about three months of real time on BESM-6 computer are spent.**

BESM-6

Mean performance – up to 1 Mflop/s

Frequency – 10 MHz , RAM – 32768 words

Supercomputer SKIF MSU - Chebyshev

*60 Tflop/s, 1250 processors Intel Xeon (*4 kerns)*

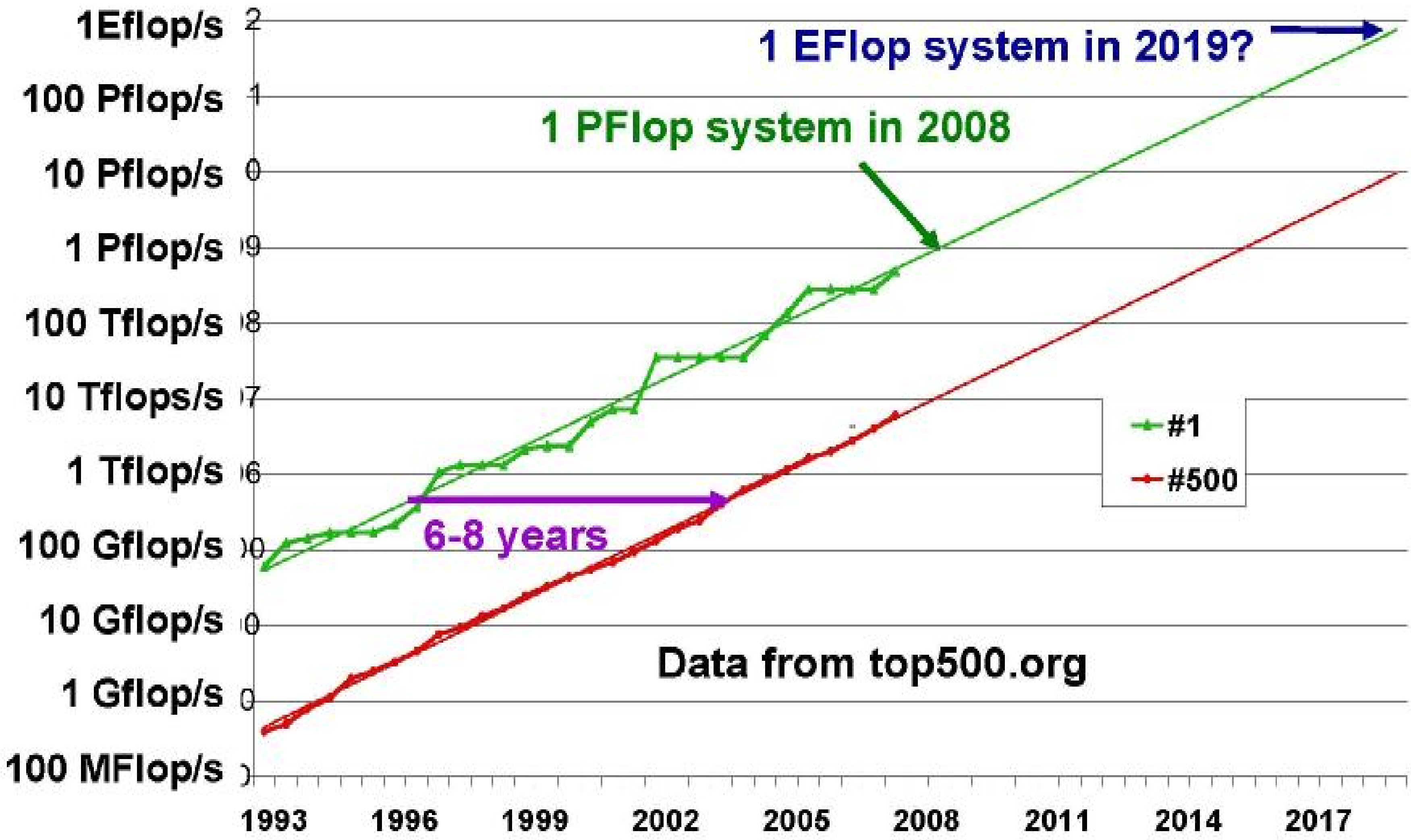
Climate model
Institute for Numerical Mathematics, RAS
(Dymnikov et al., 2005, Volodin and Diansky, 2006, http://ksv.inm.ras.ru/index)

- **Coupled model. Atmospheric resolution: 2.5x2 degrees in longitude and latitude, 21 levels in vertical up to 30 km (272160 grid points). Time step: 6 min. Oceanic resolution: 1x0.5 degrees, 40 levels (3425600 grid points). Time step: 2 hours.**

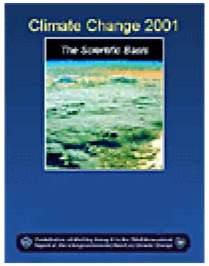
- **A set of experiments for modeling the present-day climate and assessing climate change in the future (integration for 200 – 500 years) for the 5-th IPCC Report contribution (2013).**

- **Calculations for 8 years of model time require 1 day of real time. Thus, to carry out 1 numerical experiment 1 - 2 months of real time should be spent.**

Petaflop with ~1M Cores By 2008



Slide source Horst Simon, LBNL



IPCC Reports

First Assessment Report.1990

Second Assessment Report: Climate Change 1995

Third Assessment Report: Climate Change 2001

Fourth Assessment Report: Climate Change 2007

Fifth Assessment Report: Climate Change 2013

T. Reichler, J. Kim. How well do coupled models simulate today's climate? – BAMS, 2008, 303 – 311.

TABLE 1. Climate variables and corresponding validation data. Variables listed as "zonal mean" are latitude–height distributions of zonal averages on twelve atmospheric pressure levels between 1000 and 100 hPa. Those listed as "ocean," "land," or "global" are single-level fields over the respective regions. The variable "net surface heat flux" represents the sum of six quantities: incoming and outgoing shortwave radiation, incoming and outgoing longwave radiation, and latent and sensible heat fluxes. Period indicates years used to calculate observational climatologies.

Variable	Domain	Validation data	Period
Sea level pressure	ocean	ICOADS (Woodruff et al. 1987)	1979–99
Air temperature	zonal mean	ERA-40 (Simmons and Gibson 2000)	1979–99
Zonal wind stress	ocean	ICOADS (Woodruff et al. 1987)	1979–99
Meridional wind stress	ocean	ICOADS (Woodruff et al. 1987)	1979–99
2-m air temperature	global	CRU (Jones et al. 1999)	1979–99
Zonal wind	zonal mean	ERA-40 (Simmons and Gibson 2000)	1979–99
Meridional wind	zonal mean	ERA-40 (Simmons and Gibson 2000)	1979–99
Net surface heat flux	ocean	ISCCP (Zhang et al. 2004), OAFLUX (Yu et al. 2004)	1984 (1981) –99
Precipitation	global	CMAP (Xie and Arkin 1998)	1979–99
Specific humidity	zonal mean	ERA-40 (Simmons and Gibson 2000)	1979–99
Snow fraction	land	NSIDC (Armstrong et al. 2005)	1979–99
Sea surface temperature	ocean	GISST (Parker et al. 1995)	1979–99
Sea ice fraction	ocean	GISST (Parker et al. 1995)	1979–99
Sea surface salinity	ocean	NODC (Levitus et al. 1998)	variable

on a grid-point basis with the observed interannual variance, and averaging globally. In mathematical terms this can be written as

$$e_{vm}^2 = \sum_n \left(w_n \left(\overline{s}_{vmn} - \overline{o}_{vn} \right)^2 / \sigma_{vn}^2 \right), \tag{1}$$

where $\overline{s}_{vmn}$ is the simulated climatology for climate variable (v), model (m), and grid point (n); $\overline{o}_{vn}$ is the corresponding observed climatology; w_n are proper weights needed for area and mass averaging; and σ_{vn}^2 is the interannual variance from the validating observations. The normalization with the interannual variance helped to homogenize errors from different regions and variables. In order to ensure that different climate variables received similar weights when combining their errors, we next scaled e^2 by the average error found in a reference ensemble of models—that is,

$$I_{vm}^2 = e_{vm}^2 \Big/ \overline{e_{vm}^2}^{\,m=20C3M}, \tag{2}$$

where the overbar indicates averaging. The reference ensemble was the present-day CMIP-3 experiment. The final model performance index was formed by taking the mean over all climate variables (Table 1) and one model using equal weights,

$$I_m^2 = \overline{I_{vm}^2}^{\,v}. \tag{3}$$

The final step combines the errors from different climate variables into one index. We justify this step by normalizing the individual error components prior to taking averages [Eqs. (1) and (2)]. This guarantees that each component varies evenly around one and has roughly the same variance. In this sense, the individual I_{vm}^2 values can be understood as rankings with respect to individual climate variables, and the final index is the mean over all ranks. Note that a very similar approach has been taken by Murphy et al. (2004).

RESULTS. The outcome of the comparison of the 57 models in terms of the performance index I^2 is illustrated in the top three rows of Fig. 1. The I^2 index varies around one, with values greater than one for underperforming models and values less than one

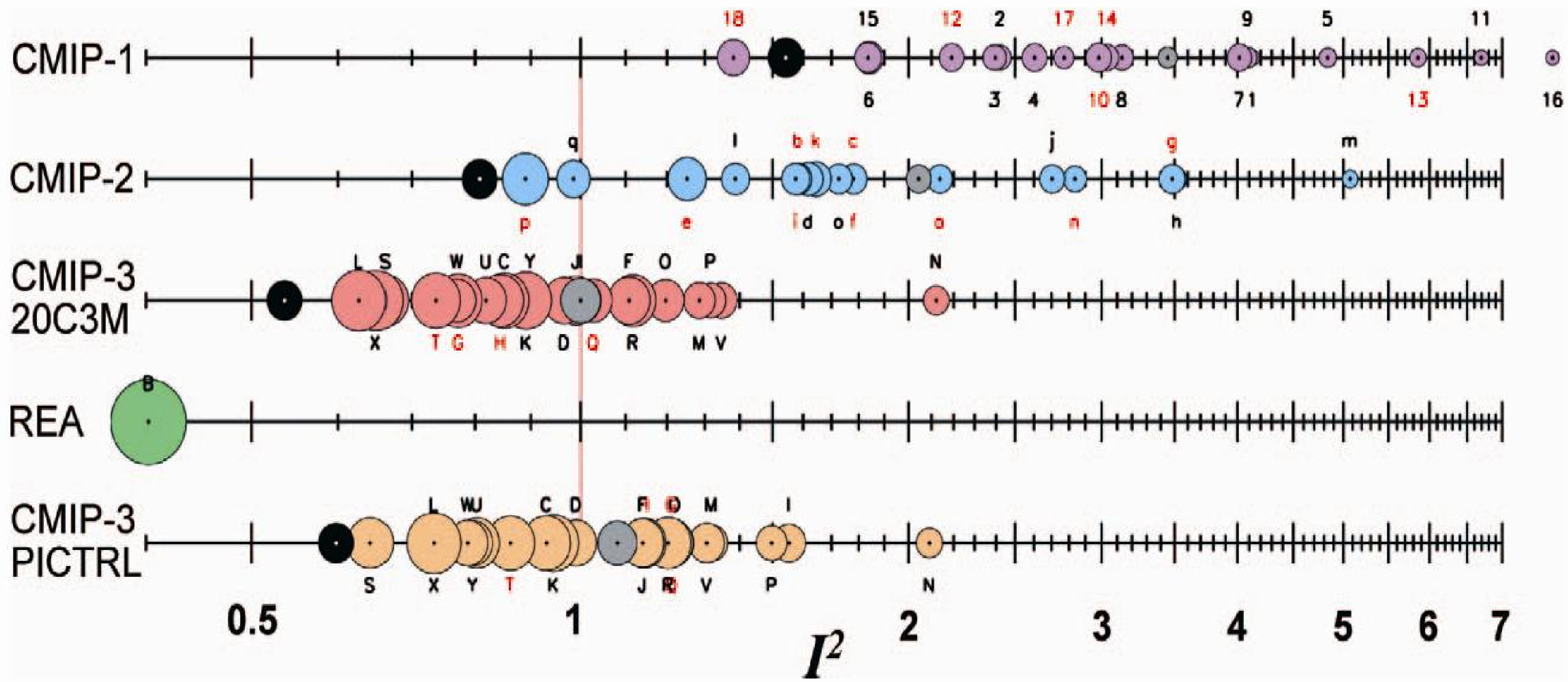


FIG. 1. Performance index I^2 for individual models (circles) and model generations (rows). Best performing models have low I^2 values and are located toward the left. Circle sizes indicate the length of the 95% confidence intervals. Letters and numbers identify individual models (see supplemental online material at doi:10.1175/BAMS-89-3-Reichler); flux-corrected models are labeled in red. Grey circles show the average I^2 of all models within one model group. Black circles indicate the I^2 of the multimodel mean taken over one model group. The green circle (REA) corresponds to the I^2 of the NCEP/NCAR reanalyses. Last row (PICTRL) shows I^2 for the preindustrial control experiment of the CMIP-3 project.

During the last 30 years the performance of supercomputers increased 10^6 times (from 10^6 to 10^{12} Flop/s).

Computational expenses to carry out numerical experiments for modeling climate and climate change are also nearly 10^6 times increased (mainly, due to long-term – up to hundreds model years – simulations).

Now, ensemble calculations (with the sample length – up to 10^3 numerical experiments) are claimed and this requires the use of petaflop supercomputers.

The horizontal resolution of the majority of climate models, results of which were used in the 4-th IPCC Report (2007) is about 200 km.

The progress achieved in the development of supercomputers and computational technologies suggests that the climate modeling community is now ready to start with the development of models, the typical resolution of which is enough to explicitly describe mesoscale (2 – 200 km) non-hydrostatic processes on the whole Earth.

WCRP
World Climate Research Programme

World Modelling Summit for Climate Prediction

WMO IOC ICSU International Council for Science

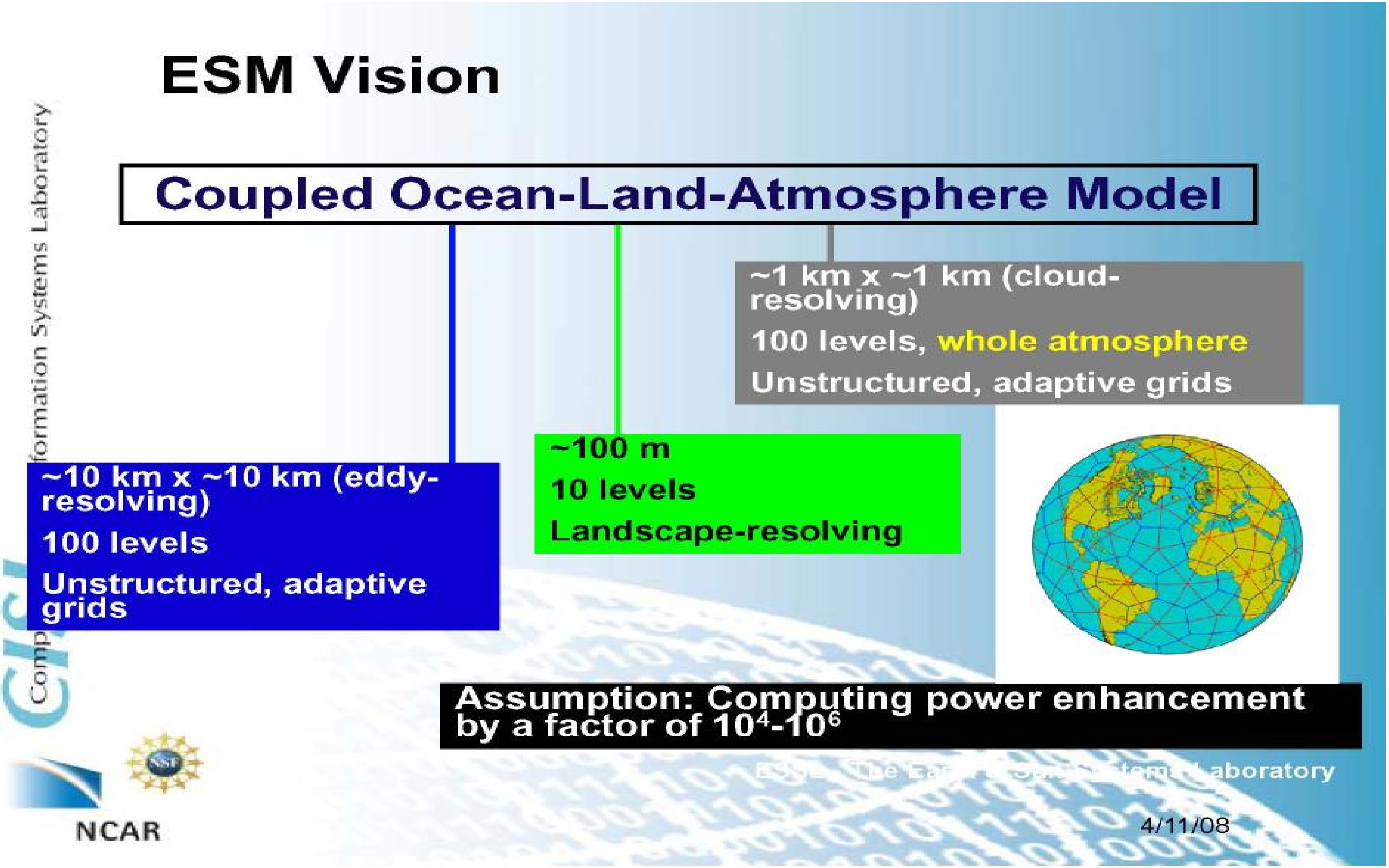
ECMWF, Reading, May 6 – 9, 2008

http://www.ecmwf.int/publications/cms/get/ecmwfnews/1213113497484

Revolutionary Perspective:
from climate models to
Earth System Models

Earth System Model

R. Loft. The Challenges of ESM Modeling at the **Petascale**



Mesoscale processes

- **Weather systems smaller than synoptic scale systems (~ 1000 and more km) but larger than microscale (< 1 km) and storm-scale (~ 1 km) cumulus systems.**
- **Horizontal dimensions: from about 2 km to several hundred kilometers.**
- **Examples of mesoscale weather systems: sea and lake breezes, squall lines, katabatic flows, mesoscale convective complexes.**
- **Vertical velocity equals or exceeds horizontal velocities in mesoscale meteorological systems due to non-hydrostatic processes.**

Subclasses

Mesoscale processes are divided into 3 subclasses (Orlanski, 1975):

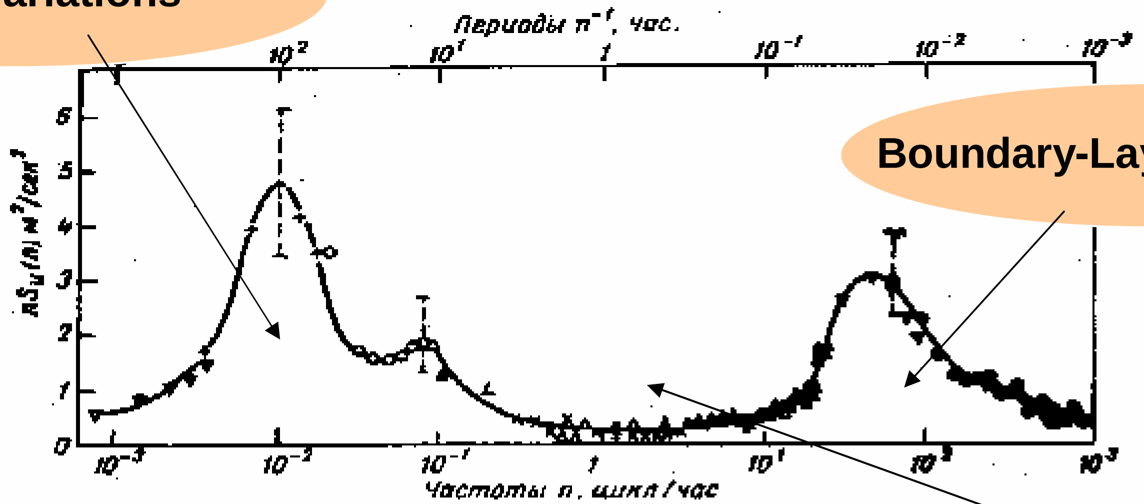
- **Meso-gamma 2-20 km, deals with phenomena like thunderstorm convection, complex terrain flows (at the edge to microscale), precipitation bands**
- **Meso-beta 20-200 km deals with phenomena like sea breezes, lake effect snow storms, polar cyclones**
- **Meso-alpha 200-2000 km fronts, deals with phenomena like squall lines, mesoscale convective systems (MCS, a large cluster of storms), tropical cyclones at the edge of synoptic scale**

PROBLEMS

- **Mechanical and thermal properties of snow cover and ground**
- **Vegetation, e.g. root system, as a regulator of evaporation**
- **River flow and associated processes**
- **Equations closure**
- **Coefficients**
- **Initial conditions (data assimilation)**
- ……..

Synoptic variations

Boundary-Layer turbulence



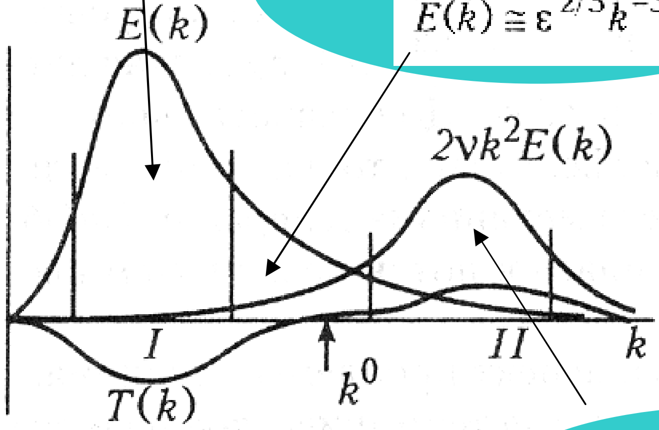
Спектр скорости ветра в приземном слое атмосферы [по Ван дер Ховену (1957), n — частота, $S_u(n)$ — спектральная плотность.

Mesoscale processes

Energy range

Inertial range

$E(k) \cong \varepsilon^{2/3} k^{-5/3}$



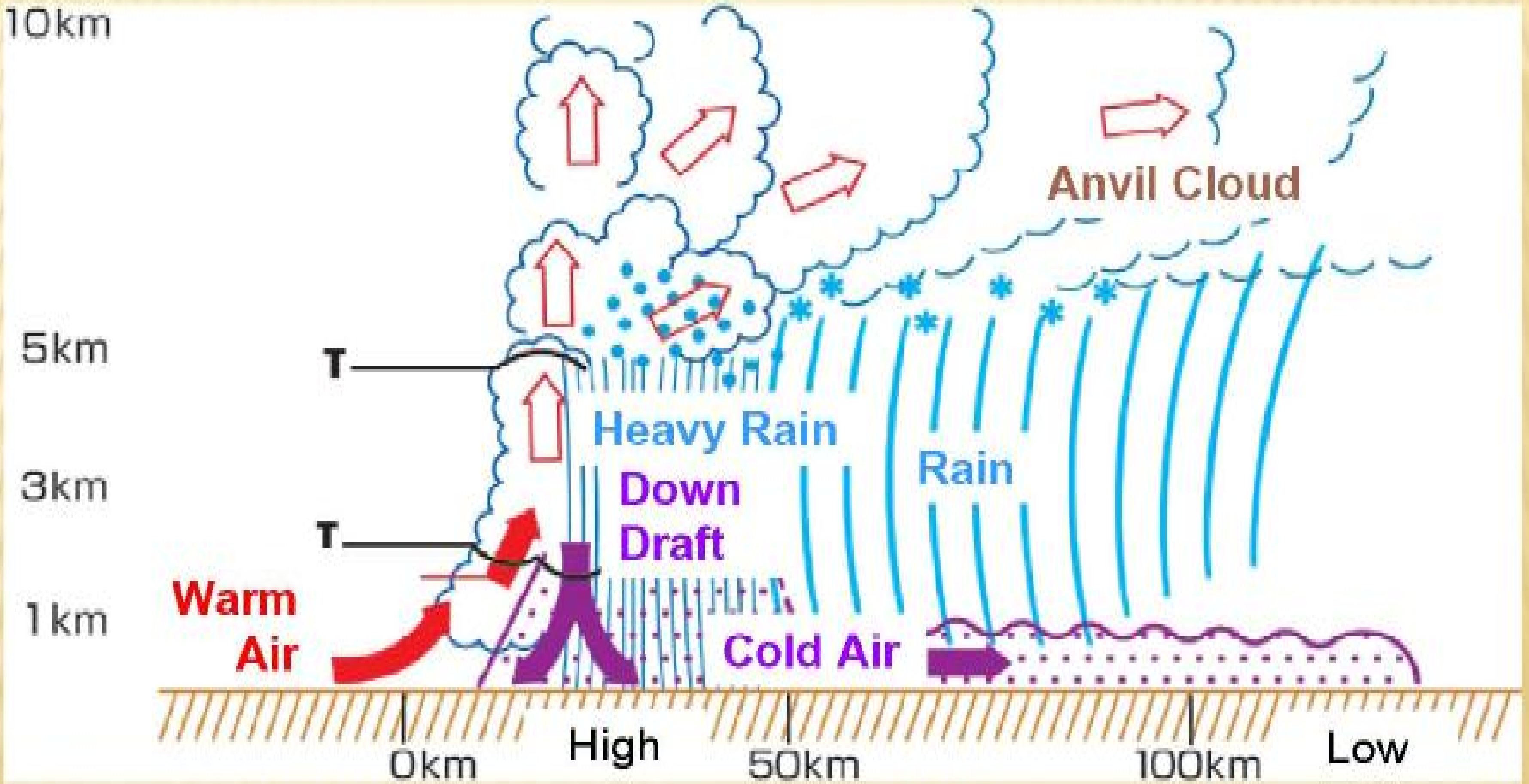
Dissipation range

$$a(x_i,t) = \tilde{a}(x_i,t) + a'(x_i,t) + a''(x_i,t)$$

$$\overline{a}(x_i,t) = \int G(x_i - x_i')a(x_i',t)dx_i'$$

$$\overline{a}(x_i,t) = \tilde{a}(x_i,t) + a'(x_i,t)$$

Structure of Cloud Cluster in the Tropics



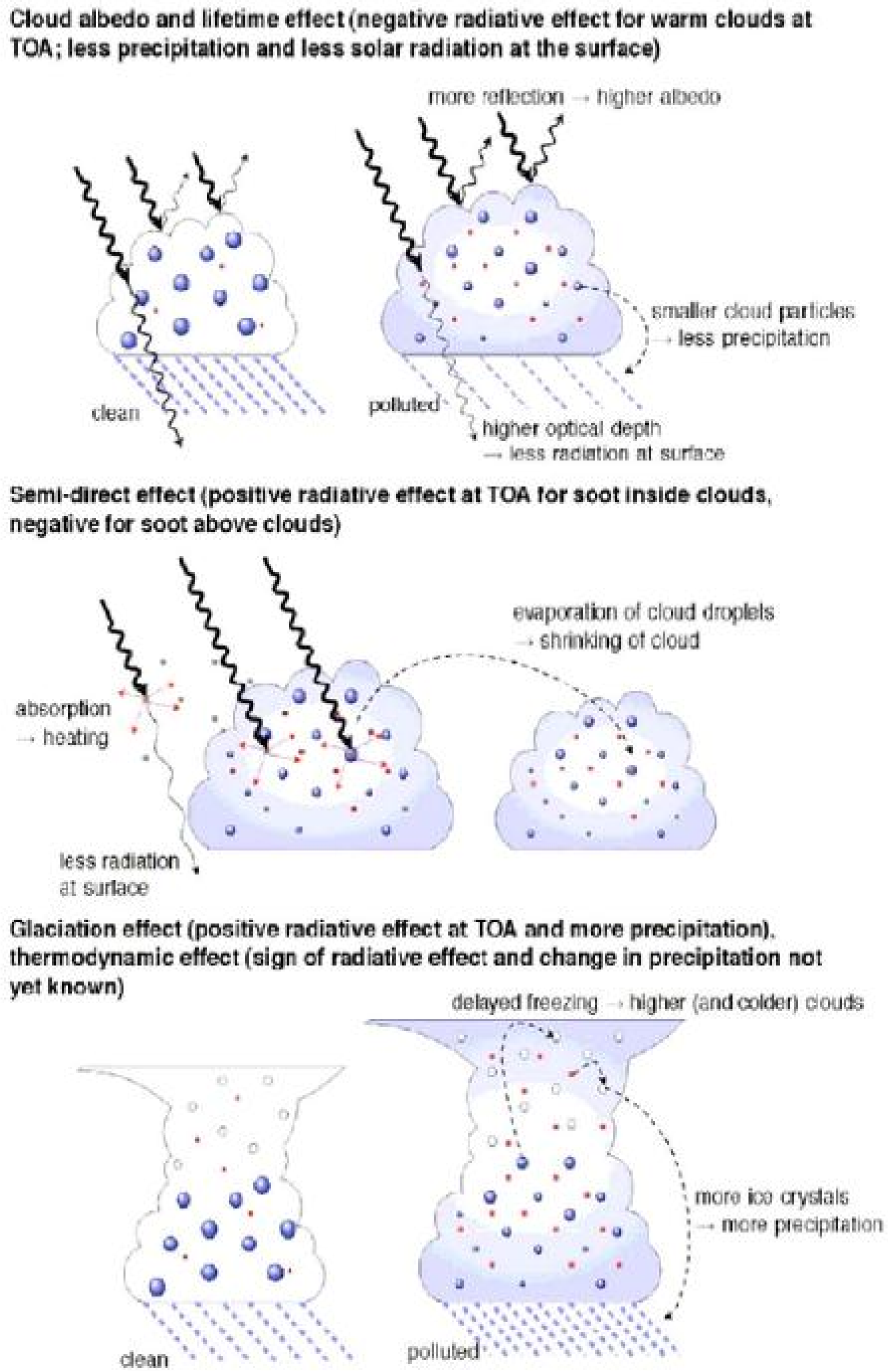
Cloud Streets (R. Rotunno, 2007)

Aerosols and Climate

Aerosols interact with clouds and the hydrological cycle by acting as cloud condensation nuclei and ice nuclei.

A larger number of cloud condensation nuclei increases cloud **albedo** and reduces **precipitation efficiency**, which result in a reduction of the global annual mean net radiation at the top of the atmosphere.

These effects may be partly offset by **evaporation** of cloud droplets due to absorbing aerosols and/or by **more ice nuclei.**



Dust storm (Stratford, Texas, USA, April 18, 1935: NOAA George E. Marsh Album)

Снежные бури

Буря мглою небо кроет,
Вихри снежные крутя;
То, как зверь, она завоет,
То заплачет, как дитя,
То по кровле обветшалой
Вдруг соломой зашумит,
То, как путник запоздалый,
К нам в окошко застучит.

А. Пушкин, «Зимний вечер» (1825)

ç == А. Саврасов «Зимняя ночь» (1869)

Snow drift

The storm wind covers the sky
Whirling the fleecy snow drifts,
Now it howls like a wolf,
Now it is crying, like a lost child,
Now rustling the decayed thatch
On our tumbledown roof,
Now, like a delayed traveler,
Knocking on our window pane.

A. Pushkin, «Winter evening» (1825)

ç == A. Savrasov «Winter night» (1869)

Large-scale hydro-thermodynamics of the atmosphere

$$\frac{du}{dt} - \left(f + \frac{u}{a} \mathrm{tg}\, j \right) v + \frac{1}{a \cos j} \left(\frac{\partial \Phi}{\partial l} + \frac{RT}{p} \frac{\partial p}{\partial l} \right) = F_u \,,$$

$$\frac{dv}{dt} + \left(f + \frac{u}{a} \mathrm{tg}\, j \right) u + \frac{1}{a} \left(\frac{\partial \Phi}{\partial j} + \frac{RT}{p} \frac{\partial p}{\partial j} \right) = F_v \,,$$

$$\frac{\partial \Phi}{\partial s} = -\frac{RT}{s} \,,$$

$$\frac{\partial p}{\partial t} + \frac{1}{a \cos j} \left(\frac{\partial p u}{\partial l} + \frac{\partial p v \cos j}{\partial j} \right) + \frac{\partial p \dot{s}}{\partial s} = 0 \,,$$

$$\frac{dT}{dt} - \frac{RT}{c_p s p} \left[p \dot{s} + s \left(\frac{\partial p}{\partial t} + \frac{u}{a \cos j} \frac{\partial p}{\partial l} + \frac{v}{a} \frac{\partial p}{\partial j} \right) \right] = F_T + e \,,$$

$$\frac{dq}{dt} = F_q - (C - E),$$

where

$$\frac{d}{dt} = \frac{\partial}{\partial t} + \frac{u}{a \cos j} \frac{\partial}{\partial l} + \frac{v}{a} \frac{\partial}{\partial j} + \dot{s} \frac{\partial}{\partial s} \,.$$

Subgrid-scale processes: parameterization

Mesoscale atmospheric model
(Miranda, 1991, Stepanenko et al., 2006)

$$\frac{\partial u p_*}{\partial t} + \frac{\partial u^2 p_*}{\partial x} + \frac{\partial v u p_*}{\partial y} + \frac{\partial \dot{s} u p_*}{\partial s} = -p_* \frac{\partial f'}{\partial x} + s \frac{\partial p_*}{\partial x}\frac{\partial f'}{\partial s} + (fv - \tilde{f}\tilde{w})\, p_* + p_* D_u \,,$$

$$\frac{\partial v p_*}{\partial t} + \frac{\partial u v p_*}{\partial x} + \frac{\partial v^2 p_*}{\partial y} + \frac{\partial \dot{s} v p_*}{\partial s} = -p_* \frac{\partial f'}{\partial y} + s \frac{\partial p_*}{\partial y}\frac{\partial f'}{\partial s} - f u p_* + p_* D_v \,,$$

$$\frac{\partial \tilde{w} p_*}{\partial t} + \frac{\partial u \tilde{w} p_*}{\partial x} + \frac{\partial v \tilde{w} p_*}{\partial y} + \frac{\partial \dot{s} \tilde{w} p_*}{\partial s} = -S_v p_* \frac{\partial f'}{\partial s} - p_* g \frac{r'}{r_s} + \tilde{f} u p_* + p_* D_w \,,$$

$$\frac{\partial p_*}{\partial t} + \frac{\partial u p_*}{\partial x} + \frac{\partial v p_*}{\partial y} + \frac{\partial \dot{s} p_*}{\partial s} = 0,$$

Turbulent closure

$$\frac{r'}{r_s} = -\left(\frac{q'}{q_s} - q_r\right), \quad f = 2\Omega \sin j \,, \quad \tilde{f} = 2\Omega \cos j \,,$$

$$\frac{\partial q' p_*}{\partial t} + \frac{\partial u q' p_*}{\partial x} + \frac{\partial v q' p_*}{\partial y} + \frac{\partial \dot{s} q' p_*}{\partial s} = -S_v \tilde{w} p_* \frac{\partial q_s}{\partial s} + p_* F_{rad} +$$

$$+ p_* \frac{L_v}{c_p}\left(\frac{p_0}{p}\right)^k (C - E) + p_* D_q \,.$$

Hydrological heterogeneity **-**
one of basic elements of the land heterogeneity

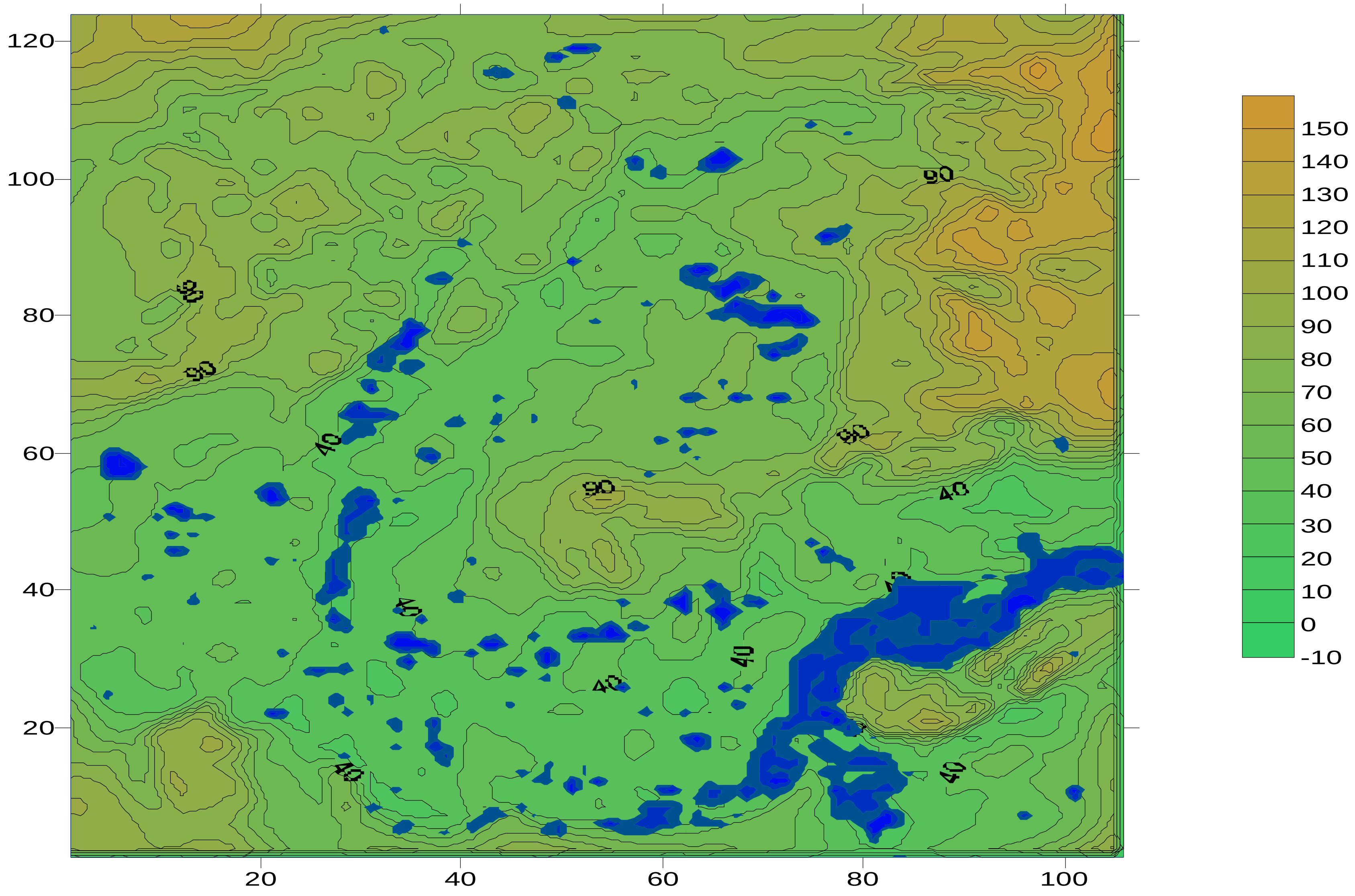
1) To account specifics of heat exchange with water objects in atmospheric models

2) To estimate changes in hydrological systems due to global warming and their impact on climate

Development and implementation in atmospheric models of improved version of computing land surface hydrological processes

One of important components is a lake model

West Siberia, 54.5-58.6° N, 63.1-66.6 ° E,
topography and inland waters, grid resolution 3.7 km



$$\frac{\partial u_i}{\partial t} = -\frac{\partial u_i u_j}{\partial x_j} - \frac{\partial p}{\partial x_i} + \frac{1}{Re}\frac{\partial^2 u_i}{\partial x_i \partial x_j} + F_i^e,$$

$$\frac{\partial u_i}{\partial x_i} = 0,$$

Navier-Stokes equations.

Approximate form of the momentum and mass conservation laws in viscous incompressible fluid.

$$F(a(x,t)) \equiv \overline{a}(x,t) = \int_{R^3} G(x - x', \Delta_f)a(x',t)dx'$$

$$\overline{\frac{\partial a(x,t)}{\partial x_i}} = \frac{\partial \overline{a}(x,t)}{\partial x_i}; \quad \overline{\frac{\partial a(x,t)}{\partial t}} = \frac{\partial \overline{a}(x,t)}{\partial t}$$

Spatial filtering

It's usually assumed that filter commutes with operator of differentiation.

It's not always the case near the boundary and/or after discretization

LES

$$\frac{\partial \overline{u}_i}{\partial t} = -\frac{\partial \overline{u}_i \overline{u}_j}{\partial x_j} - \frac{\partial \tau_{ij}}{\partial x_j} - \frac{\partial \overline{p}}{\partial x_i} + \frac{1}{Re}\frac{\partial^2 \overline{u}_i}{\partial x_i \partial x_j} + \overline{F_i^e},$$

$$\frac{\partial \overline{u}_i}{\partial x_i} = 0,$$

$$\tau_{ij} = \overline{u_i u_j} - \overline{u_i}\ \overline{u_j}.$$

Re-independent statistics of large-scale motions in turbulent flows (*observation and high-Re DNS data*) gives us hope of possibility:

1. To neglect the viscous term.

2. To find closure:

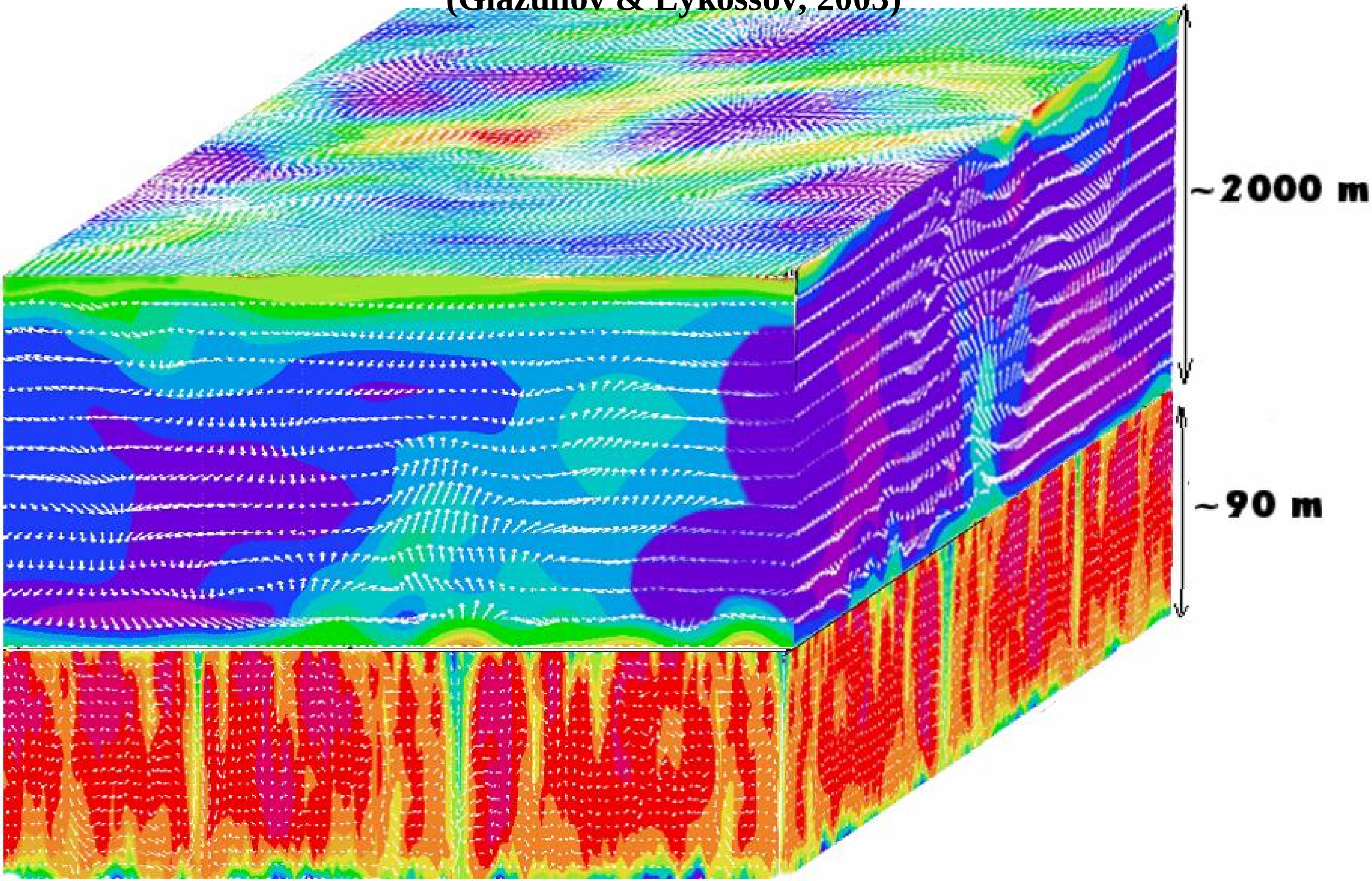
$t_{ij} \approx T_{ij}(\overline{u}_k, \overline{u}_l, \overline{u}_m)$

Central problem of LES modeling. Universal approach isn't known.

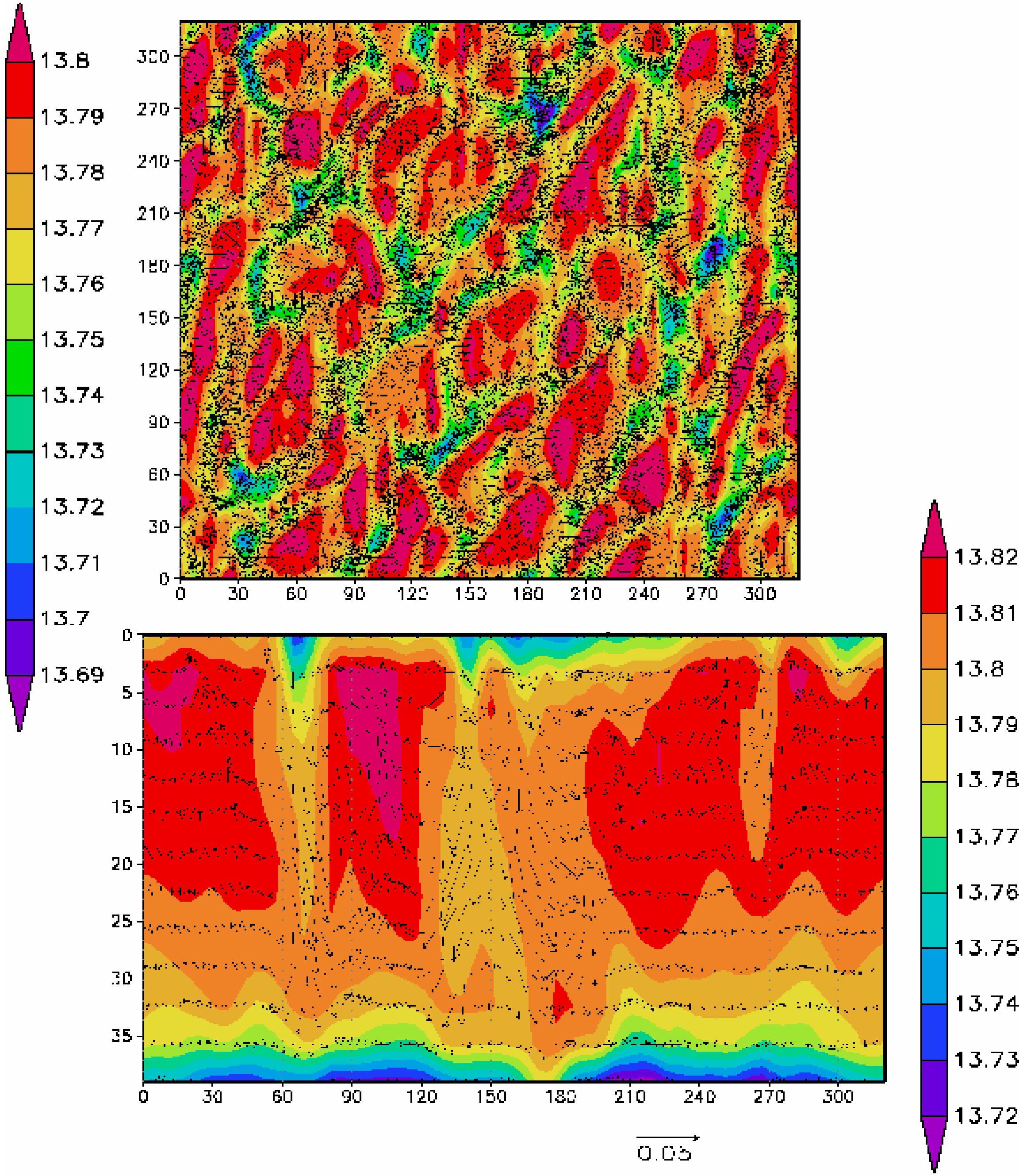
The most difficult in anisotropic wall-bounded flows

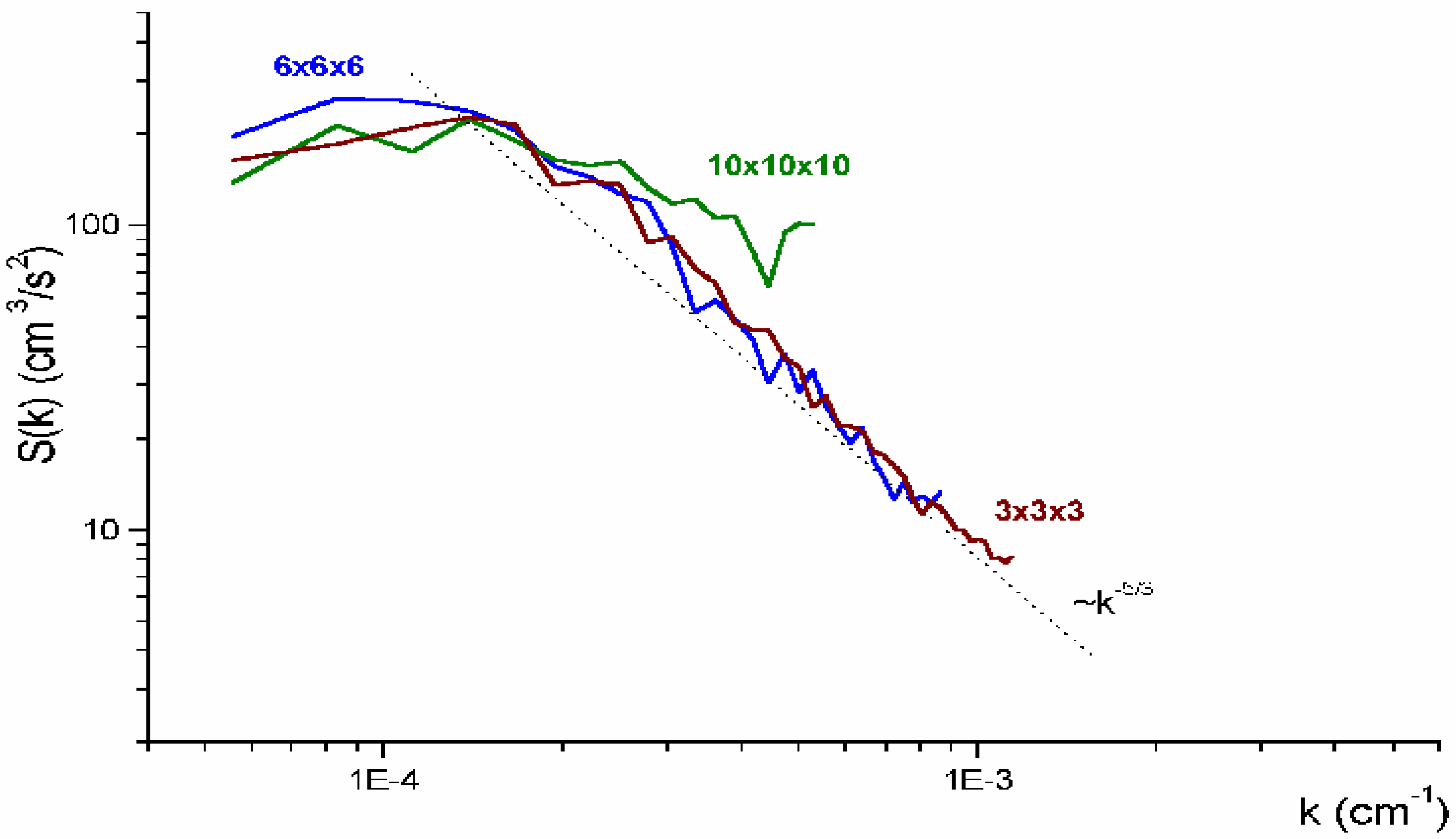
(if the energy production range isn't strongly separated from dissipation range and/or inertial range can't be resolved by the numerical model)

Large-eddy simulation of interaction of ocean and atmospheric boundary layers
(Glazunov & Lykossov, 2003)



Modelling of convective circulation in the upper oceanic layer





Spectra of kinetic energy calculated using results of large-eddy simulation of the convective upper oceanic layer under different spatial resolution (m^3)

Summary

1. The further development of climate models requires an explicit description of mesoscale processes (resolution, detailed representation of inhomogeneous underlying surface, etc.).
2. It means that the hydrostatic approximation should be replaced by the non-hydrostatic formulation.
3. New parameterizations of subgrid-scale processes should be developed (e.g., accounting for secondary circulations, stochastic processes, etc.).
4. The computational “environment” should be also revisited: numerical schemes (unstructured grids, in time - explicit, semi-implicit or fully implicit?), parallel algorithms, effective implementation on multi-processor computational systems, etc.

Performance of model code (Intel -fast, Covertown 2.66GHz), Vl. Voevodin

Real performance
Mflops

THANK YOU

FOR YOUR ATTENTION!